Indian J. Phys. **52B**, 369-378 (1978)

Semi-diurnal anisotropy during cosmic ray intensity fluctuations

R. PRASAD

Department of Physics, K. D. College, Simbhaoli (Ghaziabad), U.P.

AND

R. S. YADAV

Department of Physics, Aligarh Muslim University, Aligarh-202001

(*Received* 20 *September* 1977, *revised* 27 *January* 1978)

The average characteristics and nature of the responsible anisotropy in space of the semi-diurnal component of solar daily variation is investigated during the period of statistically significant smaller amplitude cosmic ray intensity fluctuations using the data from low and middle latitude neutron monitoring stations. Best value of spectrum exponent m in the rigidity spectrum P^m and most probable value of the amplitude and phase of the anisotropy of the cosmic ray intensity in the interplanetary space are determined. The spectrum exponent (m) ranges from $+0{\cdot}4$ to $+1{\cdot}0$ when the cosmic ray intensity fluctuations are almost steady within $\pm 1\%$ and $\pm 0{\cdot}6\%$. The strength of the anisotropy decreases with decreasing the amplitude of the cosmic ray intensity fluctuations and the time of maximum is almost perpendicular to the direction of average interplanetary magnetic field. An attempt is also made to discuss the results on the basis of the semi-diurnal anisotropy production mechanism models in vogue.

1. INTRODUCTION

The first positive confirmation for the extraterrestrial nature of the semi-diurnal anisotropy was reported by Rao & Sarabhai (1961) by using the crossed meson telescope. With the availability of the data from super neutron monitors having high statistical significance, Ables *et al* (1965) conclusively showed the existence of the semi-diurnal component of solar daily variation of world-wide nature having a time of maximum aligned perpendicular to the direction of interplanetary magnetic field (I.M.F.). The analysis by Ables *et al* (1965), Patel *et al* (1968) and Lietti & Quenby (1968) have also indicated that the semi-diurnal anisotropy has a positive exponent in the rigidity spectrum. Using large amount of the data from various super neutron monitors, Agrawal (1973) has summarised the detailed characteristics of the semi-diurnal anisotropy on an average basis as follows :

2. Characteristics of Average Semi-diurnal Anisotropy

For deriving the characteristics of the average semi-diurnal anisotropy, we shall consider an anisotropy in interplanetary space of the cosmic radiation represented by a spectrum of the type

$$\frac{\Delta J(P)}{J_0(P)} = P^m(\cos \Lambda)^n f(\theta) \qquad \text{for } P < P_u \quad \dots \quad (1)$$

$$= 0 \qquad \text{for } P > P \quad \dots \quad (2)$$

where P^m and $(\cos \Lambda)^n$ are the assumed variational reigidity spectrum and latitude dependence of the anisotropy. P is the rigidity in GV, Λ is the mean asymptotic latitude of the station, P_u is the upper out-of rigidity beyond which the anisotropy ceases and $f(\theta)$ is an arbitrary function of direction θ measured anti-clockwise to the east of the earth-sun line. The anisotropy $f(\theta)$ can be expanded into Fourier series as follows :

$$f(\theta) = \sum_{k=1}^{\alpha} A_k \cos [k(\theta - \phi_k)] \quad \dots \quad (3)$$

where A_k and ϕ_k are arbitrary amplitude and phase constants, and also ϕ_k is direction of viewing from which a maximum of K-th harmonic is seen. From a knowledge of the variational coefficients, Rao *et al* (1963) and McCracken *et al* (1965) have calculated the deviation $\Delta N(T)$ of the counting rate of a ground based detector at local time T from the mean value N for the above form of anisotropy :

$$\frac{\Delta N(T)}{N} = \sum_{k=1}^{\infty} A_k \times B_k \cos[k(15T - 180 - \phi_k) + (\gamma_k - kL)] \quad \dots \quad (4)$$

where $A_k \times B_k$ and $[-k\phi_k + (\gamma_k - kL)]$ represent the amplitude and phase constant of the K-th harmonic. L is the geographic longitude of the station and B_k and $(\gamma_k - kL)/k$ are the relative amplitude and phase correction to be applied for the deflection in the geomagnetic field. McCracken *et al* (1965) and Shea *et al* (1968) have tabulated the relative amplitude B_k and the phase correction in hours $(\gamma_k - kL)/15k$ for a number of neutron monitoring stations for ten values of spectrum exponent $m(+0{\cdot}6$ to $-1{\cdot}5)$ for diurnal and semi-diurnal components of daily variation. Agrawal (1973) has calculated these correction factors for semi-diurnal component of daily variation for 9 values of $m(+2{\cdot}0$ to $-1{\cdot}0)$ for a number of neutron monitoring stations for different upper cut-off rigidities.

3. Data Analysis

The pressure corrected cosmic ray intensity data accumulated during the year 1967 (ascending phase of the solar activity) at six super neutron monitoring stations (Table 1) which essentially sample the cosmic ray particles from directions close to the equatorial plane of the earth are used to determine the characteristics of the average semi-diurnal anisotropy during smaller amplitude cosmic ray intensity fluctuations. The data of these six stations for the period 1967 was received from the World Data Centre C-2 (Dr. M. Wada, WDC-C2 for Cosmic Rays, Cosmic Ray Laboratory, The Institute of Physical and Chemical Research, 7–13, Kaga-1. Itabashi, Tokyo, 173, Japan). Days of large world wide variations, large solar flare increases and large Forbush decreases are excluded from the analysis. The physical characteristics of the neutron monitoring stations and their location sites are summarised in Table 1.

The hour to hour changes $\Delta I_i = I_{(i+1)} - I_i$, where $i = 1, 2, 3, \ldots, 24$ (i is the number of one hourly time intervals) of neutron monitoring intensity were calculated for the all days in the year 1967 (except days of large solar flares and Forbush decreases) and at each of the 6 stations considered. Then the following 6 groups of days which recorded the following hour to hour changes of intensity : $\Delta I_i \leqslant 0{\cdot}6\%$, $\leqslant 1\%$, $\geqslant 1\%$ and $-\Delta I_i \leqslant 0{\cdot}6\%$, $\leqslant 1\%$, $\geqslant 1\%$ are shorted out for each station. The number of days observed in each group and for each station are also given in Table 1. The averaged hourly values in each group after correcting for long term variations are subjected to harmonic analysis (Yadav & Naqvi 1973) to calculate the amplitude and phase of the semi-diurnal anisotropy at each station. By using relative amplitude B_2 and phase correction in hours $(\gamma_2 - 2L)/15 \times 2$, provided by Agrawal (1973) the observed amplitude and phase of the semi-diurnal anisotropy are being corrected for the deflection in geomagnetic field for 9 values of $m(+2{\cdot}0$ to $-1{\cdot}0)$ to obtain 9 anisotropy vectors in space corresponding to 9 values of spectrum exponent m at each station. By a best fit method, the spectrum exponent m, the mean amplitude A_0 and the space direction of maximum ϕ_0 are then derived separately for each of the 6 groups of days. In all our calculations we assume that the maximum rigidity (Pu) beyond which the anisotropy ceases is equal to 200 GV and a $\cos^2\Lambda$ dependence for the amplitude of semi-diurnal anisotropy.

4. Estimation of Spectral Exponent (m) and Most Probable Anisotropy Vector

The best value of spectrum exponent m can be estimated from a number of observations imposing the condition that there must be a minimum variance between observations as determined by χ^2 statistics. The normalised variance (χ^2) for a spectrum exponent m is given by

$$\chi^2(m) = \frac{1}{6} \sum_{i=1}^{6} \left[\left(\frac{A_i(m) - A_0(m)}{A_0(m)} \right)^2 + \left(\frac{\phi_i(m) - \phi_0(m)}{\phi_0(m)} \right)^2 \right] \quad \ldots (5)$$

Table 1. List of stations and number of days analysed

Sl. No.	Station	Geogr. Coord.		Altitude (m)	Vertical cut-off rigidity (GV)	Mean Asymptotic Coord.		Number of days which recorded the following hour to hour changes in N.M intensity					
		Lat. (Deg.)	Long. (Deg.)			Lat. (Deg.)	Long. (Deg.)	$\Delta I_t \leqslant 0{\cdot}6\%$	$\Delta I_t < 1\%$	$\Delta I_t \geqslant 1\%$	$-\Delta I_t \leqslant 0{\cdot}6\%$	$-\Delta I_t \leqslant 1\%$	$-\Delta I_t \geqslant 1\%$
1.	Calgary	51·08	245·91	1130	1·09	28	269	172	300	21	172	296	25
2.	Dallas	32·78	263·20	208	4·35	25	316	190	309	26	191	313	22
3.	Deep River	46·10	282·50	145	1·02	27	319	284	325	10	263	323	12
4.	Inuvik	68·35	226·27	21	< 0·18	47	233	172	311	23	148	310	24
5.	Kiel	54·33	10·13	54	2·29	30	60	143	319	10	143	322	7
6.	Sulphur Mt.	51·20	244·39	2283	1·14	27	270	169	311	20	160	300	31

where $A_i(m)$ and $\phi_i(m)$ are the amplitude and phase in interplanetary space obtained for i-th station after correction for geomagnetic effects and $A_0(m)$ and $\phi_0(m)$ are the corresponding mean values in interplanetary space obtained for 6 stations for a spectrum exponent m. The variance $\chi^2(m)$ versus m is plotted in Figure 1 separately for each of the six groups of days considered. The minimum variance gives the best choice of m along with the most probable value of the amplitude and phase of the semi-diurnal anisotropy. The best fit value of m, the mean

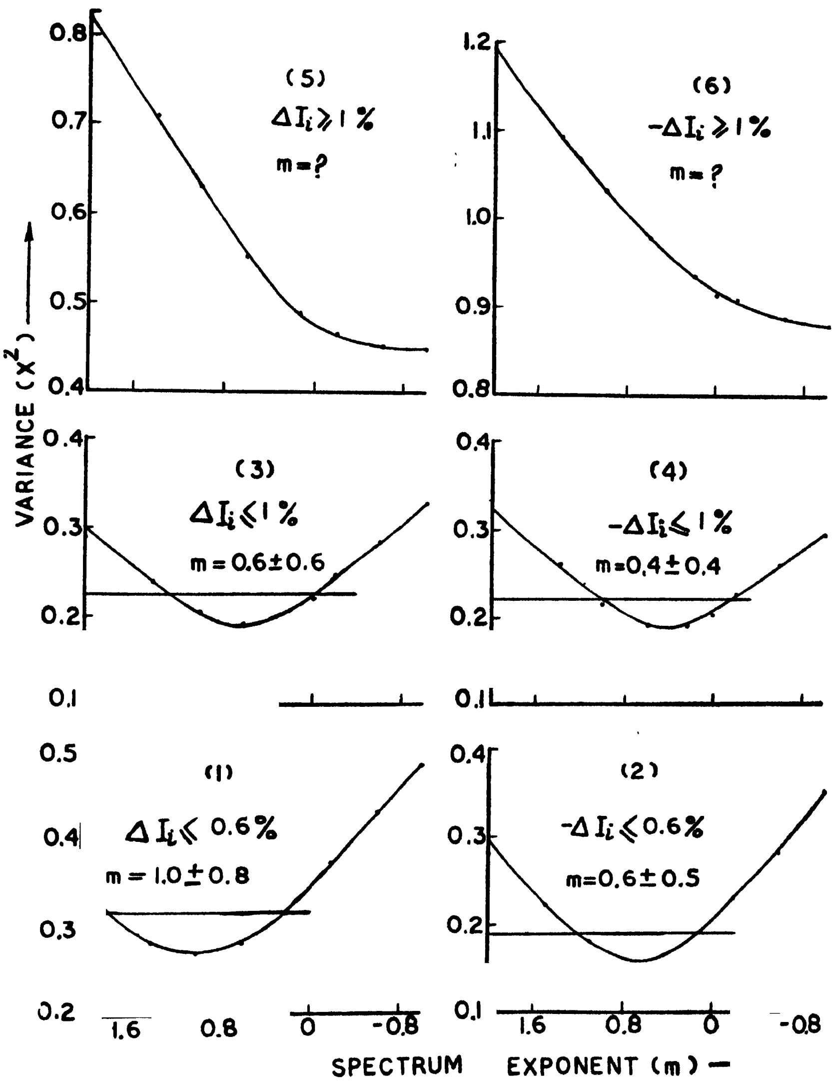

Fig. 1. The relationship between the Variance χ^2 in the observed semi-diurnal anisotropy vector for 6 Stations and the exponent m defining the rigidity dependence of the anisotropy.

amplitude and mean direction of maximum in interplanetary space thus obtained are listed in Table 2 for each of the six groups of days considered.

5. Results and Discussion

From figure 1 and Table 2 it is noted that (i) For the periods $\pm\Delta I_t \leqslant 0{\cdot}6\%$ and $\pm\Delta I_t \leqslant 1\%$, the direction of the maximum semi-diurnal anisotropy vector is almost perpendicular to the average direction of I.M.F. and the spectrum exponent of the responsible anisotropy is positive ($0{\cdot}4\pm0{\cdot}4$ to $1{\cdot}0\pm0{\cdot}8$). These results of the present analysis do not contradict the rigidity dependence of the second harmonic with a positive exponent and a maximum flux in a direction perpendicular to the I.M.F. direction (Patel *et al* 1968, Lietti & Quenby 1968 and Agrawal 1973). These results are also in agreement with the predictions of the models of Subramanian & Sarabhai (1967) or Quenby & Lietti (1968).

Table 2. Average characteristics of the semi-diurnal anisotropy (Pu = 200 GV)

Sl. No.	Group of days which recorded the following hour to hour intensity changes	Mean Amplitude A_0 (%)	Mean space direction ϕ_0 (LT)	Spectrum exponent m
1.	$\Delta I_t \leqslant 0{\cdot}6\%$	$\cdot0022\pm\cdot0021$	3·28 h	$1{\cdot}0\pm0{\cdot}8$
2.	$-\Delta I_t \leqslant 0{\cdot}6\%$	$\cdot0095\pm\cdot0023$	4·50 h	$0{\cdot}6\pm0{\cdot}5$
3.	$\Delta I_t \leqslant 1\%$	$\cdot0091\pm\cdot0051$	3·83 h	$0{\cdot}6\pm0{\cdot}6$
4.	$-\Delta I_t \leqslant 1\%$	$\cdot0219\pm\cdot0013$	4·15 h	$0{\cdot}4\pm0{\cdot}4$
5.	$\Delta I_t \geqslant 1\%$		INDETERMINANT	
6.	$-\Delta I_t \geqslant 1\%$		INDETERMINANT	

(ii) For the periods $\pm\Delta I_t \leqslant 0{\cdot}6\%$ and $\pm\Delta I_t \leqslant 1\%$ the amplitude of the semi-diurnal anisotropy is 0·022% or less, which is very low compared to the results summarised by Agrawal (1973) for normal days. The essential requirement of both the models of Subramanian & Sarabhai (1967) and Quenby & Lietti (1968), is the existence of the increasing density of cosmic ray particles, both above and below the ecliptic plane. For amplitudes of the order 0·022%, the required density gradient perpendicular to the ecliptic plane will not be too large and may agree with the density gradient estimated from the cosmic ray intensity distribution mapped in the heliolatitude range $\pm7{\cdot}25°$ by Subramanian (1971).

(iii) The amplitude of the semi-diurnal anisotropy decreases when the amplitude is reduced of sudden increase from $+\Delta I_t \leqslant 1\%$ to $+\Delta I_t \leqslant 0{\cdot}6\%$ or of sharp decrease from $-\Delta I_t \leqslant 1\%$ to $-\Delta I_t \leqslant 0{\cdot}6\%$. This behaviour was also observed in the case of the diurnal anisotropy during the smaller amplitude cosmic ray intensity fluctuations (Prasad & Yadav 1977). The amplitude of the diurnal anisotropy decreases with decreasing the amplitude of sudden increase and sharp decrease.

(iv) For the period $\pm\Delta I_t \geqslant 1\%$, the spectrum exponent is indeterminant. Hence the determination of the anisotropy is not possible by the method, employed by us as well as by other investigators.

6. Conclusion

On the basis of the detailed observational evidence presented above and reported earlier (Prasad & Yadav 1977) we concluded that for the period of smaller amplitude fluctuations the anisotropy of the cosmic ray intensity in interplanetary space responsible for the observed diurnal and semi-diurnal variations are rigidity dependent with a positive spectrum exponent. In each case (diurnal or semi-diurnal) the amplitude of the anisotropy decreases with decreasing the amplitude of the cosmic ray intensity flucutations. The directions of both of the anisotropies (diurnal and semi-diurnal) for the period considered are as summarised by other investigators for normal days on an average basis. The results of the present analysis are best explained by the perpendicular cosmic ray density gradient models proposed by Subramanian & Sarabhai (1967) and Quenby & Lietti (1968) and the density gradient perpendicular to the ecliptic plane, required to explain the observed amplitude of the semi-diurnal variation may be in agreement with the density gradient estimated by Subramanian (1971).

Acknowledgments

The authors are thankful to all the investigators whose data have been used for the present analysis. They are also thankful to Dr. S. P. Agrawal, Vikram Space Physics Centre, A.P. Singh Univessity, Rewa (M.P.)for providing the correction factors for the effect of geomagnetic bending and width and declination of the asymptotic cone of acceptance of the detector. The facilities provided by the Department of Physics and Computer Centre, A.M.U., Aligarh are gratefully acknowledged.

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